ESTABLISHMENT OF BLASIUS FLOW IN AN OPEN CHANNEL

by

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United States
Naval Postgraduate School

THESIS

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ABSTRACT

The objective of this thesis was to simulate steady, uniform, laminar flow over a plane surface with zero pressure gradient. Design parameters and requirements for the flow field and construction of the free surface water channel are discussed. Data acquisition was accomplished by means of the Hydrogen Bubble Technique; and, once acquired was used to obtain a normalized velocity profile. An uncertainty analysis on the acquisition method and a comparison of the experimental results with the solution obtained by Blasius are presented.

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NOMENCLATURE

δ	boundary layer thickness
Δx	distance between time lines measured downstream
f	functional variable for the nondimensionalized coordinate system
F	Froude number
g	acceleration due to gravity
h	depth of water in the channel
m	pulse wire pulse repetition rate
m_d	pulse wire pulse duration
η	nondimensionalized vertical distance
R_x	Reynold's number along a plane surface
R	Reynold's number based on plate length
S	scale factor
u	average instantaneous downchannel velocity
U	uniform stream velocity
v	vertical component of velocity
$W_{\Delta x}$	uncertainty in Δx
W_m	uncertainty in m
W_s	uncertainty in S
W_u	uncertainty in u
x	direction taken downchannel
y	direction taken vertical to the flow and perpendicular to x

ACKNOWLEDGEMENTS

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1. Introduction.

The boundary layer concept was introduced by Prandtl [1] in 1904. Four years later Blasius [2], using Prandtl's boundary layer equations, obtained a solution for steady, uniform, laminar flow, with constant fluid properties and zero pressure gradient, over a plane surface. As cited in Schlichting [3], experimental verification of Blasius' solution followed in 1924 by Burgers [4] and van der Hegge Zijnen [5], in 1930 by M. Hansen [6], and most carefully by Nikuradse [7], in 1942.

A brief review of the applicable boundary layer equations characterizing the classic Blasius problem is presented. The use of the assumptions:

(1) incompressibility,

(2) constant fluid properties,

(3) steady two-dimensional laminar flow,

(4) zero pressure gradient,

(5) and the usual boundary layer assumptions,

results in reducing the full Navier-Stokes equations to the more tractable form (Schlichting [3]),

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \nu \frac{\partial^2 u}{\partial y^2}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

Employing the similarity hypothesis advanced by Blasius [2](velocity profiles in the boundary layer are similar, see Figure 1) one has

$$\frac{u}{U} = \frac{\partial f(\eta)}{\partial \eta} = f'(\eta)$$

Where

$$\eta = \frac{y}{\delta} = \frac{y}{x} R_x^{1/2}$$

and

$$R_x = \frac{Ux}{\nu}$$

Using the stream function for uniform flow and the aforementioned definitions Blasius obtained the following normalized differential equation of the boundary layer:

$$f(\eta) f''(\eta) + 2 f'''(\eta) = 0$$

and solved it for the boundary conditions:

(1) $f'(\infty) = 1$,

(2) $f(0) = 0$,

(3) $f'(0) = 0$.

The results of Blasius' solution are illustrated graphically in Figure 2.

Over the succeeding years, subsequent investigative permutations of Blasius' original problem were made. One such permutation, under accelerated scrutiny, was the study of heat transfer through a fluid stream undergoing a liquid to solid phase transformation. The freezing of the fluid in the flow field over a plane surface was examined mathematically by Lapadula and Mueller [8] and Beaubouef and Chapman [9]. Pertinent experimental information, for the flat plate geometry, was provided by Savino and Siegel [10,11]. It was noted that Siegel and

Savino omitted the effect of the flow field in the analysis of their problem.

In order to augment the limited supply of experimental information and to include the effect of the flow field in the analysis, a thesis was undertaken by B. F. Nolan, at the Naval Postgraduate School. Nolan [12] used a flat plate similar in geometry but larger in size than was employed by his predecessors. The flow field effect was included in his analysis by assuming Blasius flow over the cooling plate which allowed the boundary layer to remain unaffected by the solid phase geometry. The establishment of the Blasius flow field for Nolan's thesis was undertaken as an independent project.

It was apparent that the two projects were interrelated the first generating construction and flow requirements for the second. The cooling plate assembly, insulation and instrumentation required that the bottom of a free surface water channel be the test section for the second proposal. This requirement eliminated the difficulties which would otherwise be generated by a leading edge, instrumentation and support assembly of a flat plate model suspended in the flow. The ice growth study further required that the boundary layer should be sufficiently large or the Reynolds number be rather small. Quantitative data acquisition has been and continues to be an inherent difficulty in low velocity water flow. Impact tubes have been impractical and hot wire or hot film methods required a relatively pure fluid medium, which was not the case in this instance. Hama and Nutant [13], in a study concerning the transition phenomenon, required low speed flows. They discarded the dye-injection method in favor of the hydrogen bubble technique (hereafter referred to as HBT) as a means of gaining qualitative and quantitative information about the flow field.

There have been a number of papers in recent years concerning the investigation of the HBT for flow visualization and measurement. Some of the more noteworthy of those reports were those of Clutter, Smith and Brazier [14] in 1959, Schraub, Kline, Henry, Runstadler and Littell [15] in 1965 and Hansen [16] in 1968. A perusal of those papers revealed that the HBT when properly employed, was capable of excellent qualitative and reasonable quantitative information. The reliability of the HBT with respect to data acquisition was a function of many variables, the more important of which were:

(1) steadiness of the flow field,

(2) generating wire diameter,

(3) electronics,

(4) photographic tenchique.

It was the objective of this thesis to design a system which would generate the desired flow conditions and to obtain a velocity profile using the HBT. The experimental velocity profile was then to be compared with the analytic solution obtained by Blasius.

2. Equipment.

The apparatus was comprised of a free surface water channel, control tank, floor tank, pump and associated piping. Driving force for the flow was provided by a Byron Jackson Company Pump Model No.08H-74. The pump took suction at a large sunken floor tank and discharged through a 6 inch diameter pipe, containing a standard ASME flange type orifice meter, and thence through a transition piece (from a circular section of 6 inch radius to a 1 square foot cross-section) into the channel. The channel was divided into three parts, the flow production section, the test section and a connecting channel. After flowing through the channel, the water entered a large control tank where the energy of the flow was dissipated. The drain from the control tank was set to maintain a constant water level in the channel for a given flowrate.

The flow production section had several features all of which contributed to the purpose of the system, that of generating a uniform laminar flow. As reported by Lumley [17], honeycomb of large length to diameter ratio could be used to effectively reduce background turbulence. The large length to diameter ratio allowed the flow to become fully developed in the cells thus to some extent damping longitudinal flow oscillations as well as those in the transverse and vertical directions. Two regions of honeycomb (L/d ratio 24 and 13.3, respectively) were used in this project and proved effective in eliminating vertical and cross channel fluctuations. Two wire screens were also placed downstream from the honeycomb material.

The screens, placed in order of increasing mesh size, in conjunction with the honeycomb helped to damp out longitudinal oscillations in the stream and produced a uniform velocity profile (see Figures 3, 4 and 5).

In addition, an adjustable gate was situated at the head of the unit and two fine mesh screens were placed downstream of the test section. The latter features, in addition to a damping board, were added to minimize surface waves.

In a study conducted by Binnie, Davies and Orkney [18], the production of a uniform stream was discussed in some detail. It was found that if care was taken to eliminate incoming disturbances and a Froude number ($F = U/\sqrt{gh}$) of 0.5 was not exceeded, the velocity profile was indeed uniform. For our purposes a maximum Froude number of 0.02 was contemplated as a design parameter. This value was not exceeded during the course of the data runs. Also, the desired uniform flows ranged from 0.5 to 2.0 inches/second implying Reynolds numbers ($R = Ul/\nu$) ranging from 4165 to 16,660, well below the critical Reynolds number for a flat plate (500,000).

The test section of the channel was 18 inches long, 11.5 inches wide and 12 inches high. The test surface had a rectangular array of holes (0.025 inches in diameter) tapped through it. These holes covered the area where the cooling plate of the associated project would be located. The array served as a means of insuring a constant head pressure over the test surface and also provided access for the HBT generating wire. A versatile traversing mechanism contained the HBT pulse wire electrode and provided a means of accurately locating the pulse wire perpendicular to the test surface. The test section including the traversing mechansim and HBT apparatus are shown in Figures 6 and 7.

The report by E. Hansen [15] was consulted frequently during the design, construction and operation of the HBT equipment. A block diagram illustrating equipment arrangement and corresponding manufacturers are shown in Figure 8. The triggered pulse amplifier, a near duplicate of the one discussed by E. Hansen, was constructed to provide pulse power to the generating wire. Fast response coupled with a wide range of voltage and current produced a good bubble line which was of prime consideration in the measurement of the velocity profile.

The photographic equipment used to record the instantaneous bubble configuration in the test section was a Polaroid-Land Camera Model 110B, including a Polaroid Close-up Lens Kit no. 550, with Polaroid 3000 speed black and white film. A scale factor (S) was obtained by comparing a submerged scale in the bubble plane with that same scale out of water. With the bottom, top and opposite side of the test section shielded from external light, the bottom was provided with an unshielded strip through which a collimated light source illuminated the bubble plane.

The stream flowed into the control tank through a portion of the connecting channel. Regulation of the control tank and the water level was done with a parabolic gate valve which provided a linear change in the flowrate with a change in gate position.

3. Procedure and Presentation of Data.

Once a steady flowrate and water level were established in the channel, necessary steps were taken to acquire a velocity profile. As stated previously, illumination of the bubble plane was provided by a collimated light source shining up through the test surface. The next step was to generate timed marker lines into the stream.

The pulse repetition rate (m) and pulse duration (m_d) were adjusted so as to give optimum line definition and spacing. Photographic requirements (f/4.57, shutter speed of 1/125 sec., close up lenses +2 and +4, range at 3 feet) were found prior to beginning the run. The use of the Polaroid-Land Camera allowed quick qualitative information on the adequacy of the photographs. Typical photographs are shown in Figure 9.

Longitudinal spacings (Δx) between marker lines (for vertical channel positions ranging from 0.0 to 1.2 inches) in 0.1 in. intervals were measured. The velocities were calculated from the formula, $u = \Delta x \cdot m \cdot S$, where, as stated previously, m is the pulse-wire pulse reption rate and S is the scale factor. To calculate the normalized velocity profile we require the quantities u/U and δ, where

$$\frac{u}{U} = \frac{\Delta x}{\Delta X}$$

and

$$\eta = y/\delta$$

The boundary layer thickness (δ) has been defined (Schlichting 3) as $y = \delta$ for $u/U = 0.99$. This corresponds to $\eta = 5.0$ or $\delta = y/5.0$. Thus, for each y, in the range indicated, normalized velocity and vertical distances were obtained through the measurement of the variables graphically defined in Figure 10.

Figure 10 is presented as a diagramatic representation of the instantaneous position of the marker lines in the bubble plane and should not be misconstrued as depicting velocity profiles. The inflection point seen in the marker lines near the wire was not representative of the flow field; but, was a characteristic phenomena exhibited by bubbles moving in the boundary layer. The presence of the inflection point may be explained as follows: the size of the bubbles generated by the pulse wire were in the order of the wire's diameter. Thus, the bubbles that collected within the wake of the cylindrically shaped wire fell in a region of the flow field where there was considerable momentum deficiency due to the presence of the wire. Since there is a vertical component of velocity within the boundary layer (Schlichting [3]) the bubbles were convected upwards and more or less parallel to the wire. An additional contribution to this convective motion came from the secondary fluid motion generated within the wake. It is therefore important to note that one should not take data very near to the generating wire and should also be extremely careful in this and other studies regarding the stability of flows as far as the inflection points are concerned. It was remarkable indeed that such a small wire could, together with the aid of the bubbles, gave the false appearance of the existence of an inflection point when, in reality, there was not one.

In following the guidelines set down by Kline and McClintock [19], and Kline, Schraub, Henry, Runstadler and Littell [14], it became apparent that the significant uncertainty in u (W_u) was the uncertainty in Δx ($W_{\Delta x}$). Since the bubbles were of sufficiently small size and photographs were taken over seventy diameters downstream of the pulse wire, bubble rise and velocity defect were minimally contributing uncertainties and therefore omitted from the analysis. Great care was taken to produce a uniform laminar flow field and to place the generating wire vertically in the stream and perpendicular to the test surface. The purpose of this was to minimize the uncertainties induced by a transverse slope in the bubble plane so that such errors could also be omitted from the analysis.

The velocity in the bubble plane was given by

$$U = \Delta X \cdot m \cdot S$$

It followed then, that

$$W_u = \sqrt{\left(\frac{\partial U}{\partial \Delta X} W_{\Delta x}\right)^2 + \left(\frac{\partial U}{\partial m} W_M\right)^2 + \left(\frac{\partial U}{\partial S} W_S\right)^2}$$

Where W_m and W_s were the uncertainties in the pulse repetition rate and scale factor, respectively. As stated by Shraub, Kline, et. al. [15] W_m and W_s may be neglected since they were small relative to $W_{\Delta x}$. Therefore,

$$W_u = \sqrt{(m \cdot S \cdot W_{\Delta x})^2} = m \cdot S \cdot W_{\Delta x}$$

Normalizing, one has

$$\frac{W_u}{U} = \frac{W_{\Delta x}}{\Delta X}$$

A typical x for the runs made with this equipment was 0.30 $\pm$ 0.033 inches (20:1). Therefore,

$$\frac{W_u}{U} = \frac{W_{\Delta x}}{\Delta X} = \frac{0.033}{0.30} = 0.11$$

or the percent uncertainty in u was 11%.

A comparison of the normalized velocity profile, reduced from the experimental data, with the Blasius solution shows a maximum deviation of 12%. Hence, it seemed reasonable to conclude that the accuracy of the apparatus at present was in accord with the calculated uncertainty.

The normalized velocity profile, obtained experimentally, was shown in Figure 11, for three different flow rates. The experimental profile appeared to be in agreement with that theoretically obtained by Blasius indicating that the desired flow field had been established.

4. Remarks and Recommendations.

A more accurate velocity profile could be obtained if the uncertainty in Δx were reduced. A sizeable reduction in this uncertainty could be achieved if there were better bubble line definition. The most aggravating contribution to the lack of a better definition is the build-up of impurities on the generating wire. This build-up generates streaming sites on the wire and limits its useful age. As a result of the streaming phenomenon we get a thicker time line and consequently a larger uncertainty interval.

The following recommendations are submitted in order to improve marker line quality and generally enhance the efficiency of the equipment:

(1) Provide the triggered pulse amplifier with a polarity reversing switch. A series of pulses of reversed polarity to the generating wire has a cleansing effect.

(2) Provide a filtering system for the water in the floor tank. This would decrease the number of impurities and may even make practical the use of a hot film device as a second means of measuring velocity.

(3) Change from Nichrome alloy wires to high tensile strength Platinum alloy wires as the Platinum wires have a longer useful lifetime and tend to resist the buildup of impurities.

(4) Replace the present power amplifier and pulse generator arrangement with a Hewelett-Packard pulse generator Model No. 214A, with 200 watt output. This pulse generator coupled with the triggered pulse amplifier should give a more versatile pulse characteristic.

(5) Construct an adjustable constant head tank ahead of the flow production section to eliminate any pump surging.

(6) Provide a calibrated V-notch weir at the end of the connecting channel as a second means of measuring flowrate. This would also tend to minimize surface waves.

(7) Try the perforated plate and rubberized hair suggested by Nutant [12], in the flow production section.

(8) See if it is feasible to apply a correction factor for bubble motion in the boundary layer. The fact that the normalized velocity profile is in excellent agreement outside the boundary layer and falls off markedly on entry into the boundary layer deems a correction factor appropriate.

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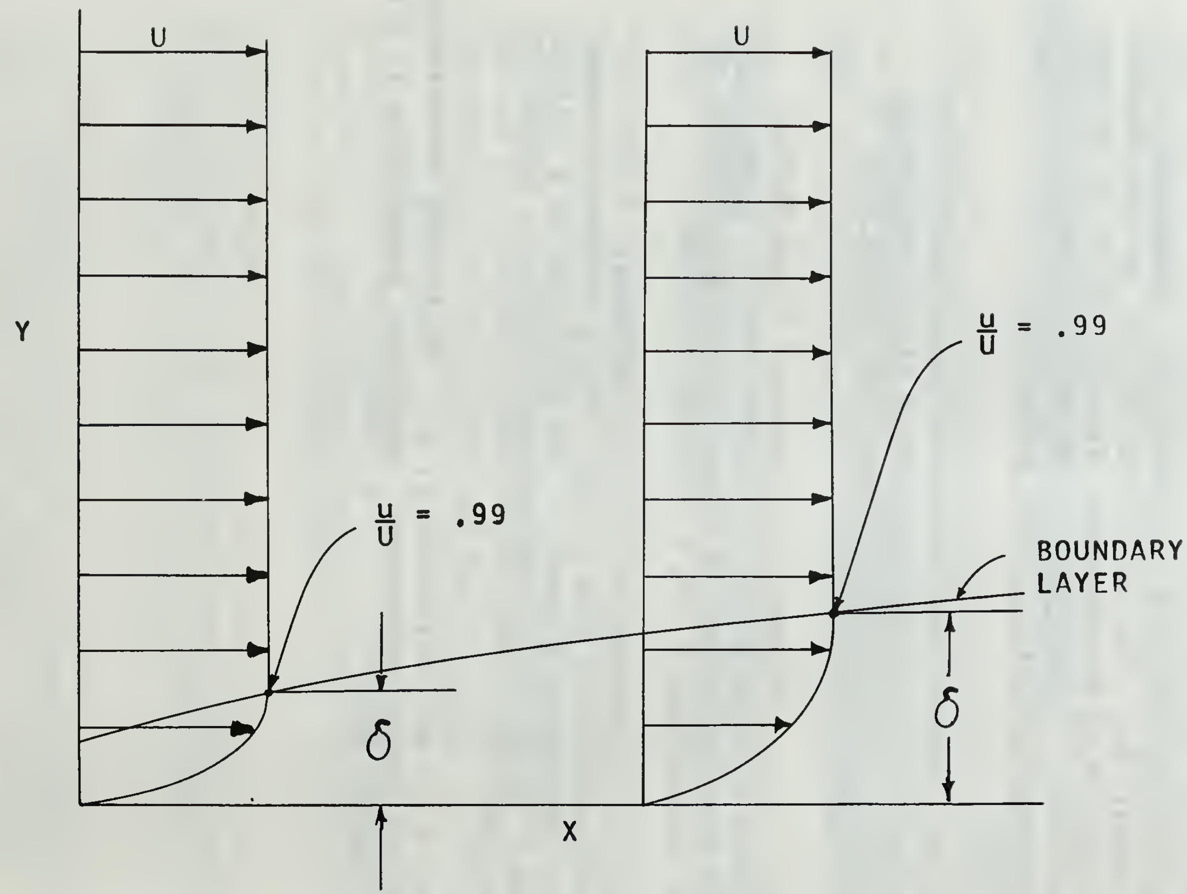


FIGURE 1. SIMILAR VELOCITY PROFILES IN THE BOUNDARY LAYER

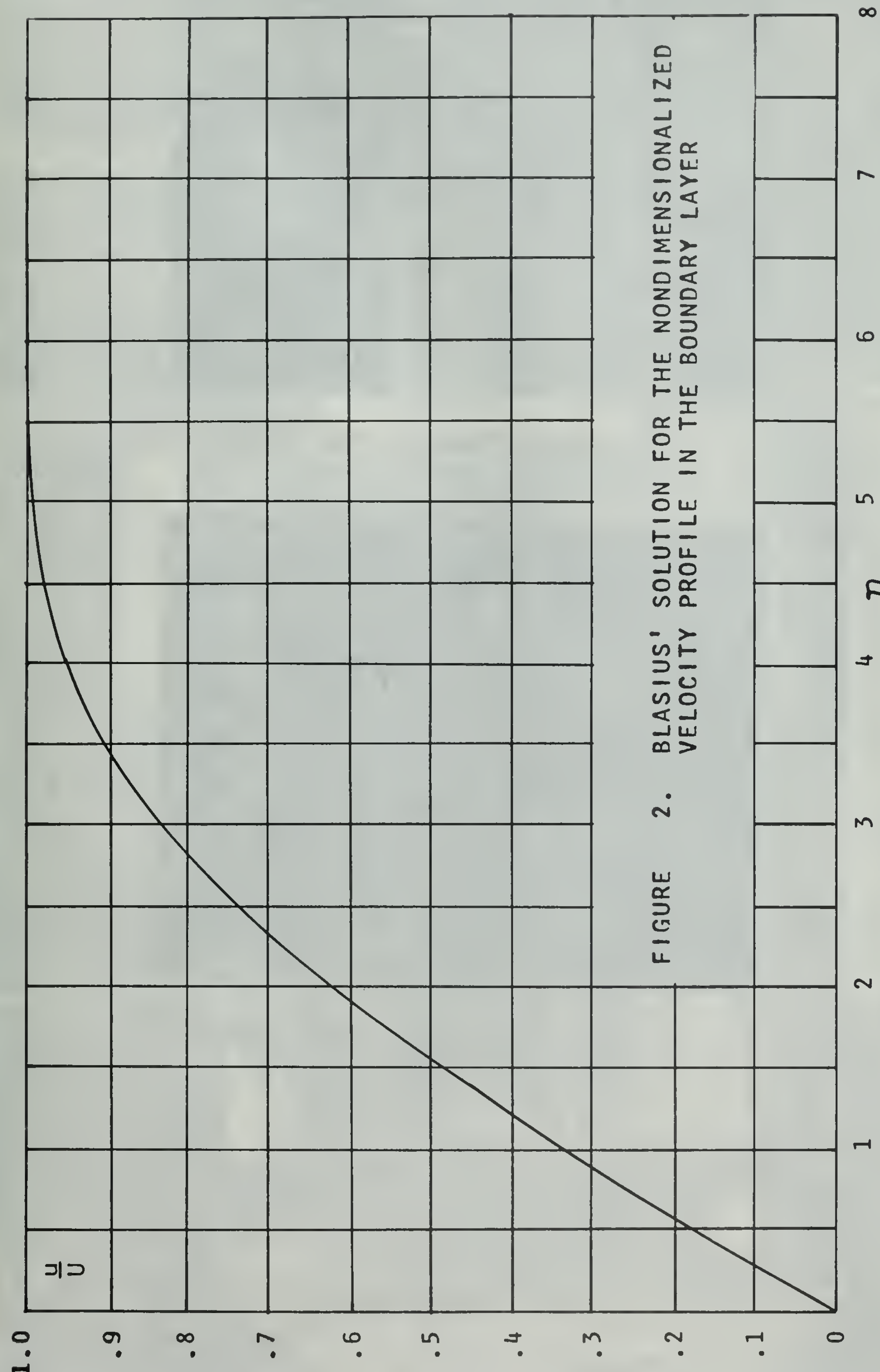
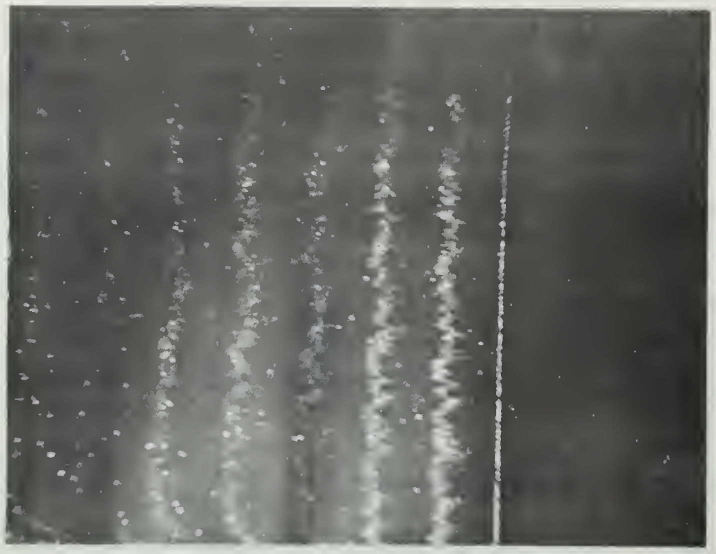
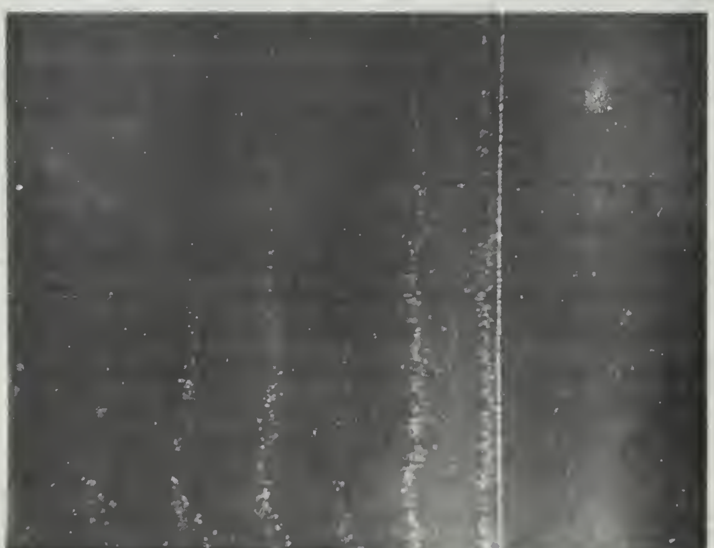


FIGURE 2. BLASIUS' SOLUTION FOR THE NONDIMENSIONALIZED VELOCITY PROFILE IN THE BOUNDARY LAYER



U = 1.25 INCHES/SECOND , m = 3.28 CPS



U = 0.81 INCHES/SECOND , m = 1.85 CPS

FIGURE 3. PHOTOGRAPHS OF UNIFORM STREAM PROFILES

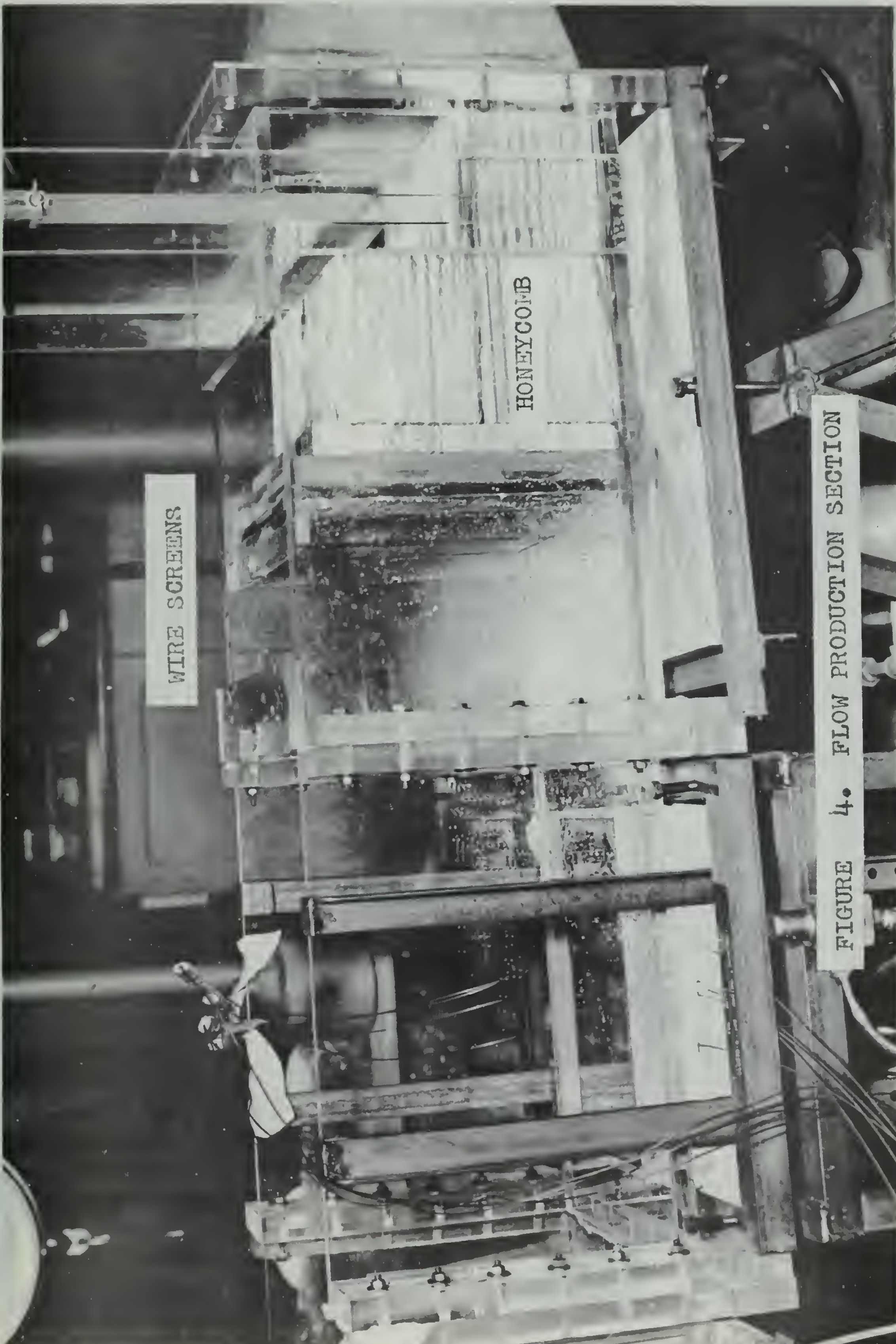


FIGURE 4. FLOW PRODUCTION SECTION

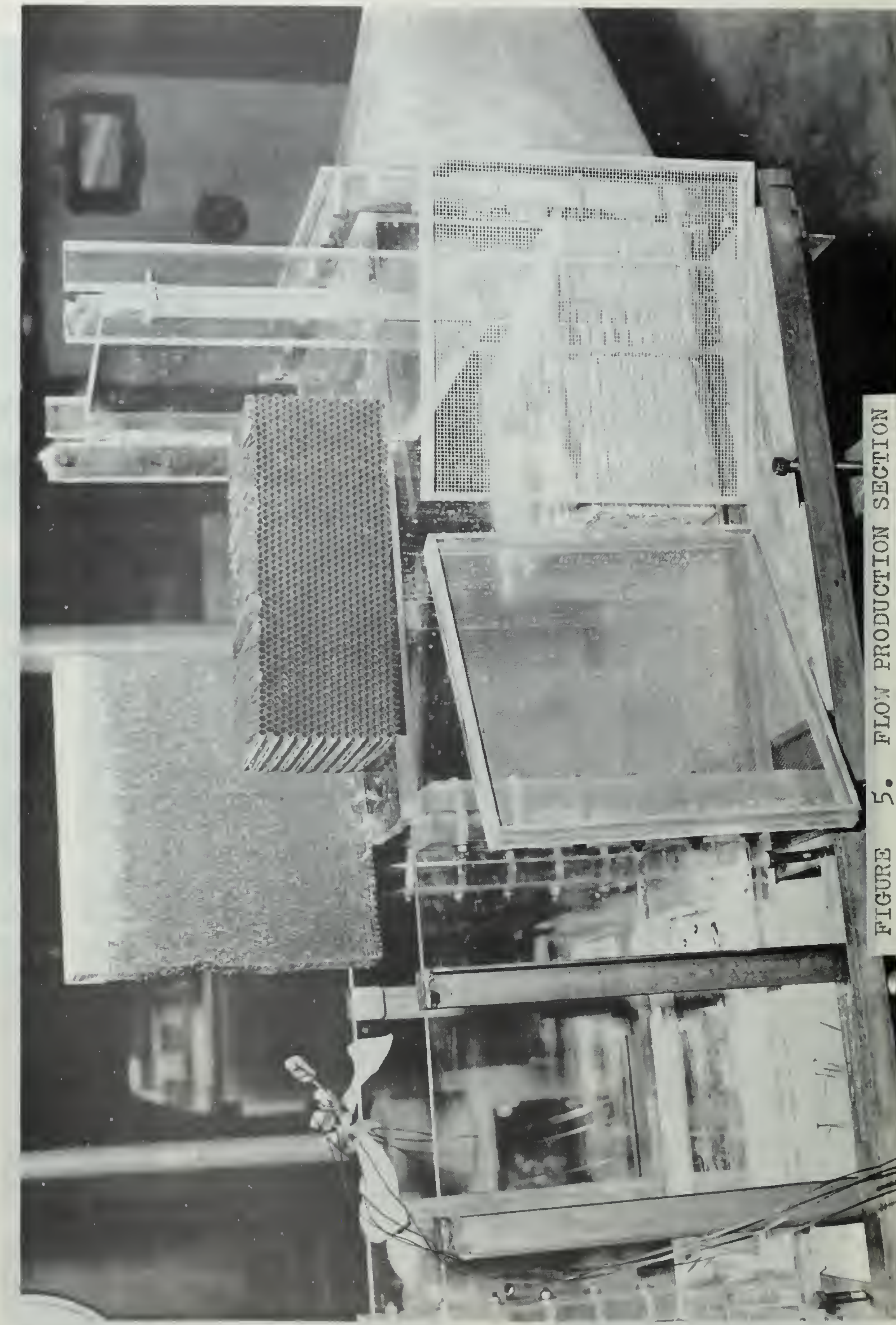


FIGURE 5. FLOW PRODUCTION SECTION

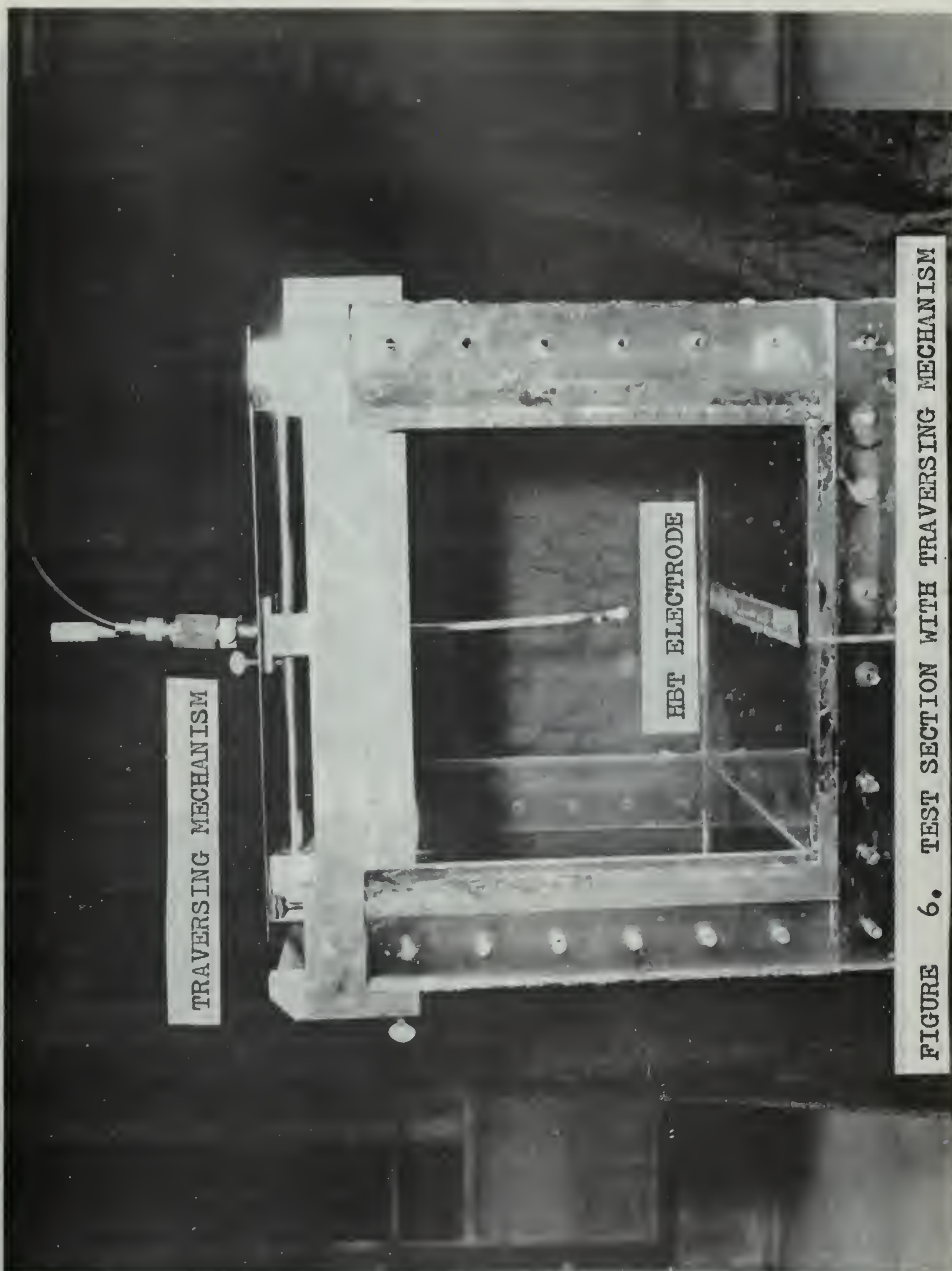


FIGURE 6. TEST SECTION WITH TRAVERSING MECHANISM

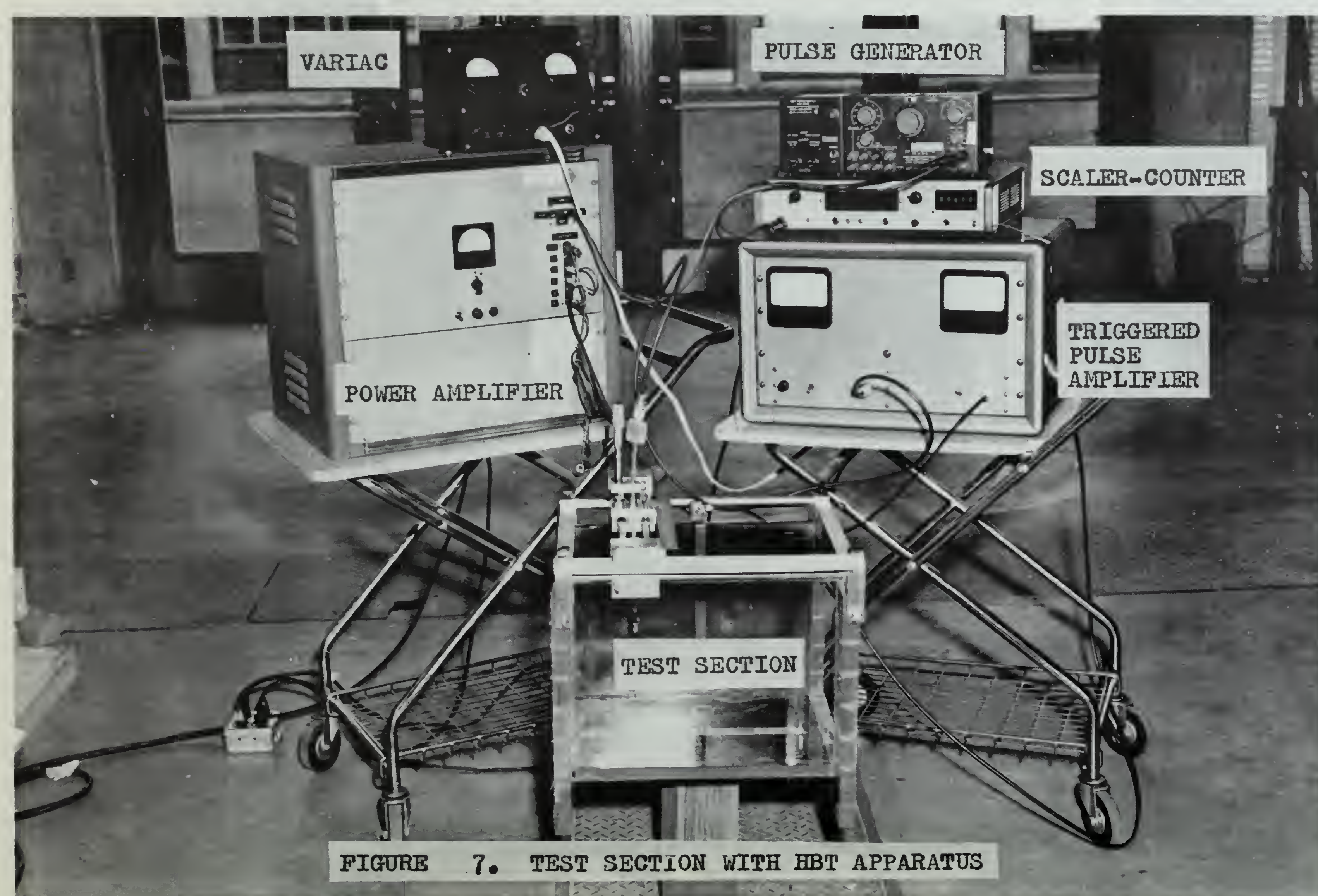


FIGURE 7. TEST SECTION WITH HBT APPARATUS

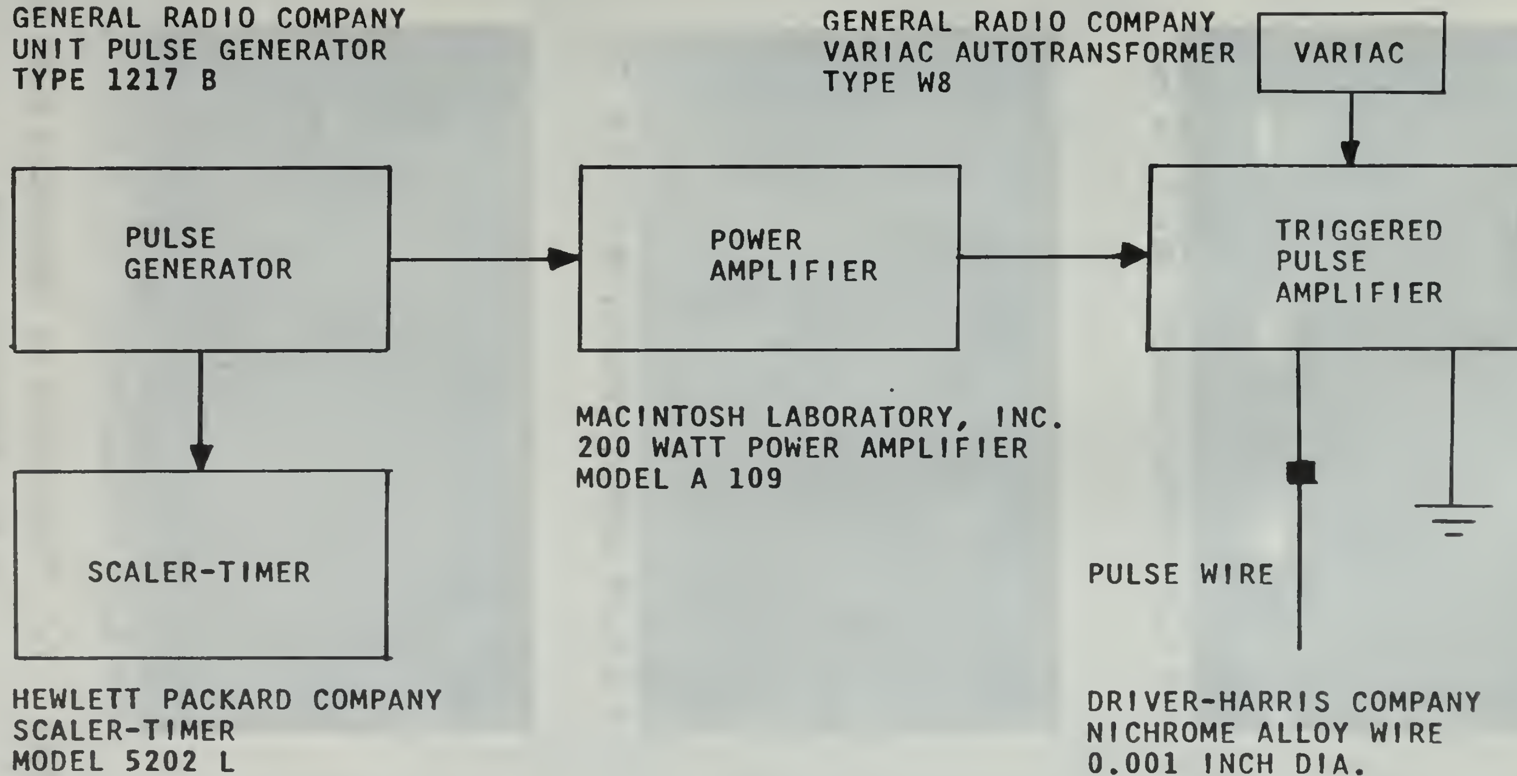
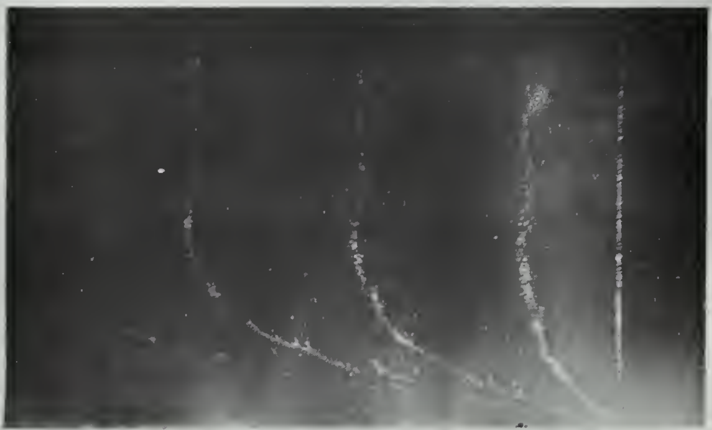


FIGURE 8. BLOCK DIAGRAM OF HYDROGEN BUBBLE GENERATING EQUIPMENT

U = 1.05 INCHES/SECOND, m = 2.78 CPS



U = 0.78 INCHES/SECOND, m = 0.835 CPS

U = 0.88 INCHES/SECOND, m = 0.835 CPS

FIGURE 9. PHOTOGRAPHS OF GENERATED TIME LINES IN THE BOUNDARY LAYER

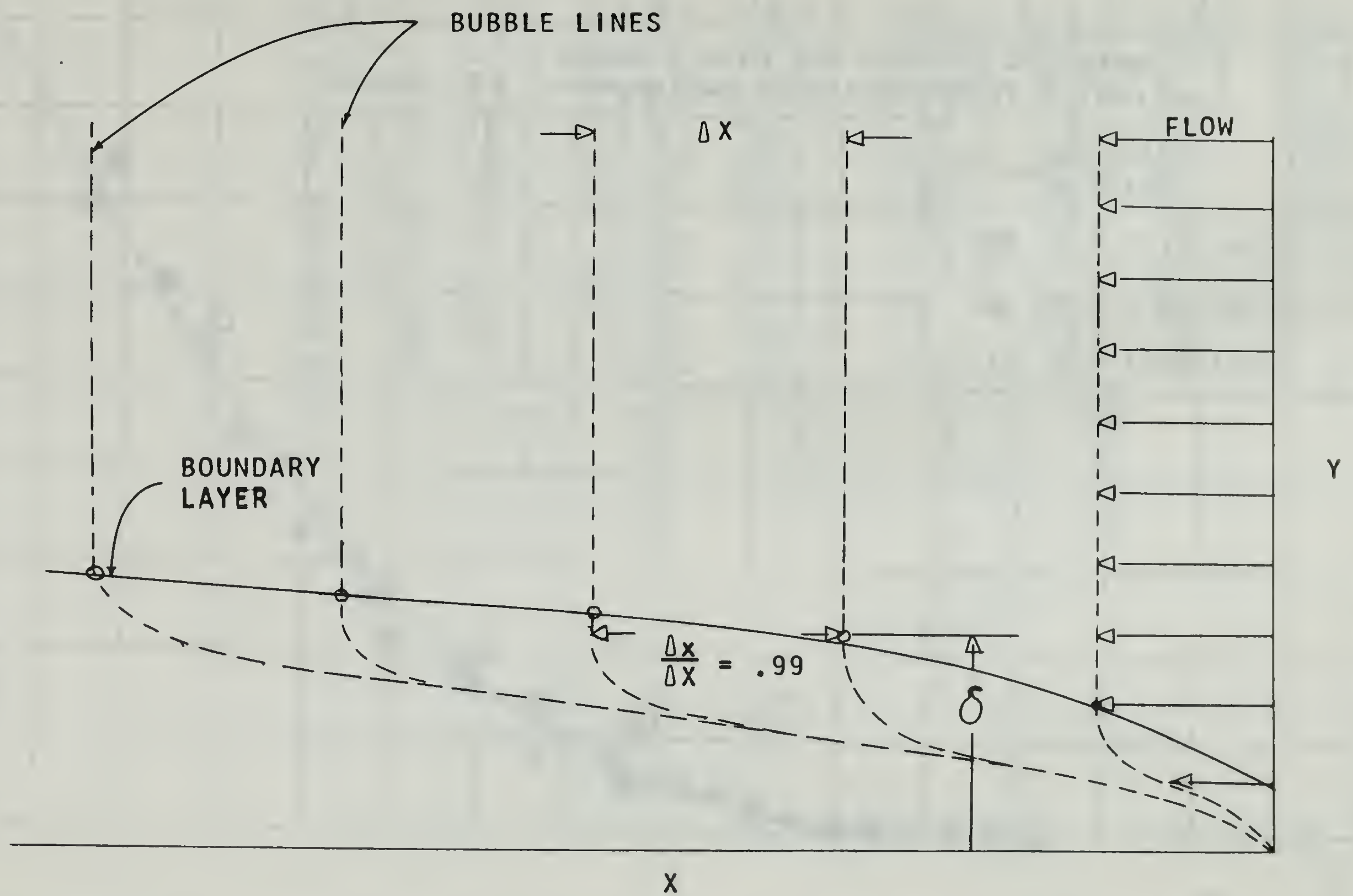


FIGURE 10. INSTANTANEOUS POSITION OF BUBBLE LINES IN THE BUBBLE PLANE

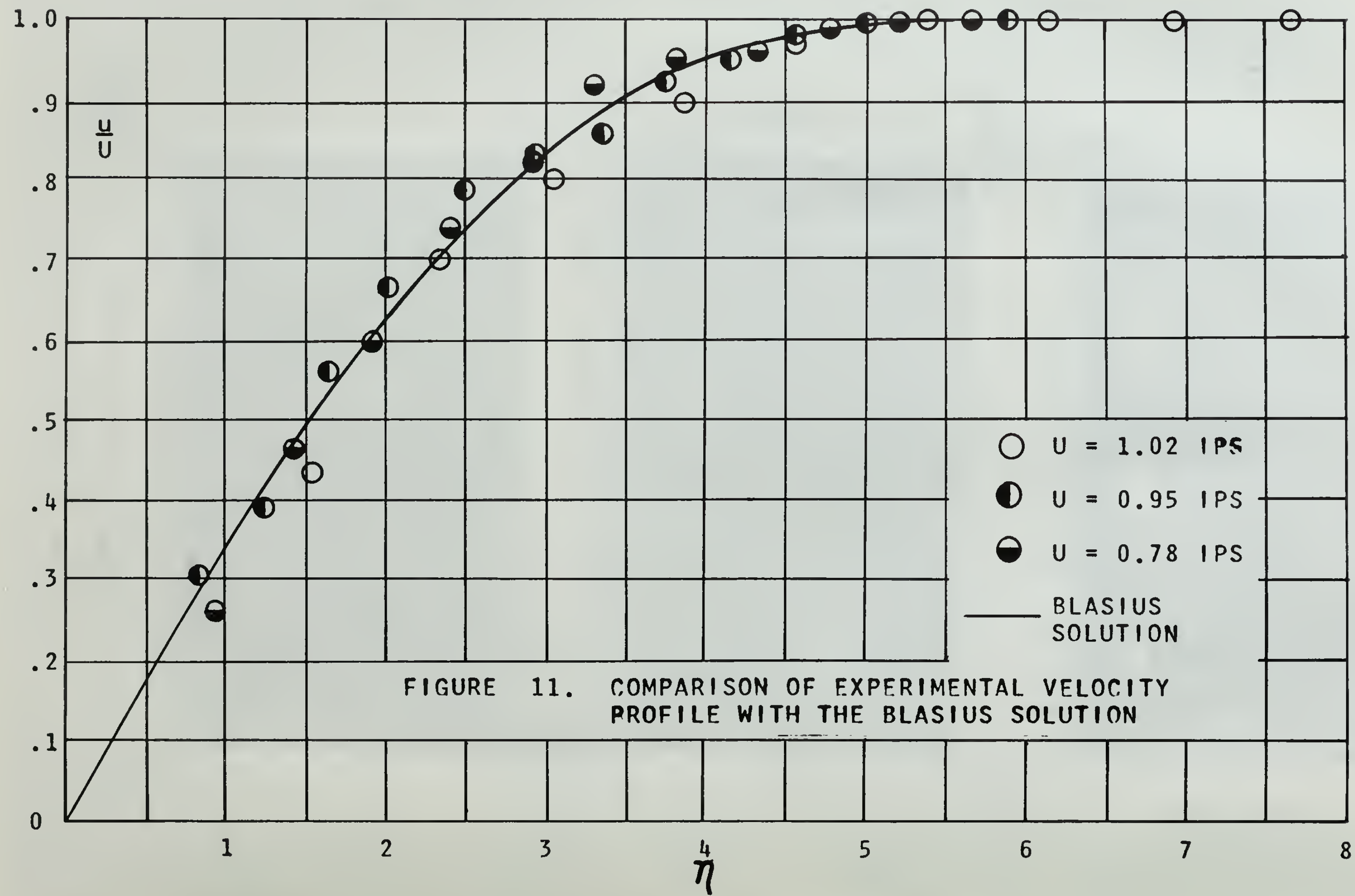


FIGURE 11. COMPARISON OF EXPERIMENTAL VELOCITY PROFILE WITH THE BLASIUS SOLUTION

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13. ABSTRACT

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14. KEY WORDS	LINK A		LINK B		LINK C	
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